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OCT Imaging up to 760 kHz Axial Scan Rate Using Single-Mode 1310nm MEMS-Tunable VCSELs with >100nm Tuning Range

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Abstract: We describe the first widely tunable, single-mode 1310nm MEMS VCSELs with >100nm tuning range, and the first application of these VCSELs to ultra-high-speed swept source OCT imaging at axial scan rates up to 760kHz.

Swept source Optical Coherence Tomography (OCT) has emerged as a powerful technique for obtaining micron scale 3D images of biological tissue [1]. Emerging applications which require real-time acquisition of high-density, high volume data sets have driven the search for commercially viable swept laser sources around 1310nm with ~40 mW output power, >100nm tuning range, and several hundred kHz or higher sweep speeds [2,3]. MEMS tunable Vertical-Cavity Surface-Emitting Lasers (VCSELs) are an ideal swept source for OCT imaging, because of their micron scale cavity length and low mirror mass enabling high sweep speeds, single-mode operation without mode hops, long dynamic coherence length [4] enabling deep imaging, and compatibility with low-cost wafer-scale fabrication and testing. Though MEMS tunable VCSELs have existed for well over a decade [5,6], limited tuning range and output power have thus far precluded application to OCT.

In this work we demonstrate record sweep rates and bandwidths from VCSEL sources by integrating a wide-gain InP-based quantum well active region with a GaAs-based fully oxidized mirror through wafer bonding, as shown in Figs. 1,2. A suspended top dielectric mirror moves through electrostatic actuation, generating tunable 1310nm laser emission as the structure is optically pumped at 980nm. A subsequent semiconductor optical amplifier (SOA) boosts power and re-shapes the spectrum before inputting to an OCT imaging system.

Figure 2 shows the static tuning curve of this device illustrating a 110nm continuous mode-hop-free tuning range. This tuning range is broader than the largest previously reported VCSEL tuning range of 65nm at 1550nm [4], and represents a factor of ~2 improvement in fractional tuning range ($\Delta\lambda/\lambda$). Figure 3 illustrates time-averaged spectra under repetitive sweeping at 380kHz (corresponding to 760kHz axial scan rate) before and after amplification, also illustrating advantageous re-shaping of the spectrum by the SOA for OCT imaging.

Figs. 4-6 illustrate OCT results obtained with the amplified MEMS VCSEL sources. Fig. 4 illustrates time-evolution of VCSEL pre- and post-amplified output power under repetitive scanning at 380kHz, along with Mach-Zehnder (MZI) interference fringes. Forward and backward scans show comparable performance, in contrast to other swept sources, enabling axial-scan rates of 760kHz. Figure 5 illustrates en-face images of a finger pad obtained from a volumetric data set consisting of 512X512 axial scans.

Measurement of the long coherence length of VCSELs at these high A-scan rates is currently limited by electronics and detector bandwidths, although we have observed >28mm coherence length at tens of kHz rates, where measurement does not require high detection bandwidth. Fig. 6 illustrates the roll-off of the OCT point spread function vs. imaging depth at 500kHz A-scan. The 6-dB roll-off at 4.5 mm imaging depth corresponds to a minimum of 9mm coherence length, limited by electronic bandwidth. Unlike other swept laser sources, which use a short cavity and intra-cavity filter, VCSELs operate with a true single-longitudinal mode instead of a set of modes. VCSELs can therefore sweep at adjustable repetition rates while maintaining superior coherence length. These results suggest that VCSELs are a superior technology for swept source OCT imaging.

Acknowledgements

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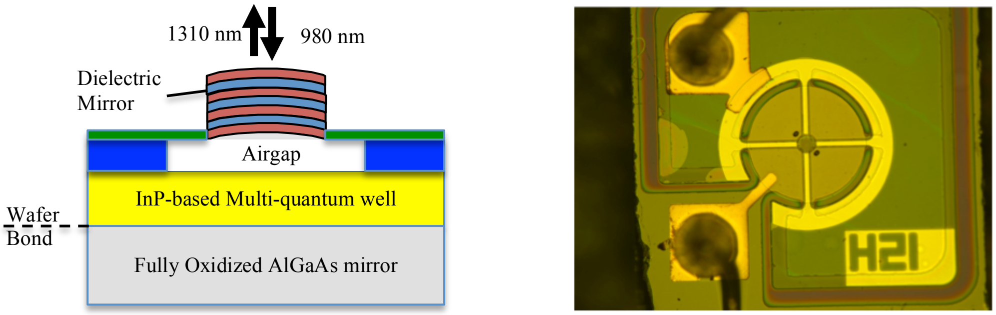

Figure 1: Device cross section (left) and top-view wire-bonded photo (right). Device employs an InP-based MQW gain region, a wafer bonded fully oxidized AlGaAs mirror, and a suspended dielectric mirror above a variable air-gap. Device is optically pumped from the top at 980 nm, and emits 1310 laser light out the same side.

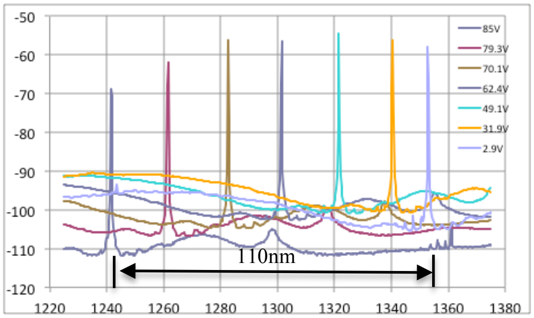

Figure 2: Example static tuning of 110nm with 85V drive.

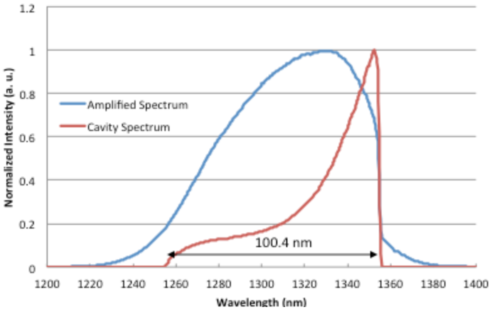

Figure 3: Time averaged spectrum under 380kHz (760kHz A-scan) sweeping over 100 nm, pre and post-amplified. ASE emission is observed outside the tuning range but is not used for imaging.

Figure 4: Oscilloscope traces of 380kHz drive signal (green), corresponding to 760kHz A-scan. Shown are laser output (red), amplified output (purple) and Mach-Zehnder clock fringes (yellow). Note nearly symmetric forward/backward scans.

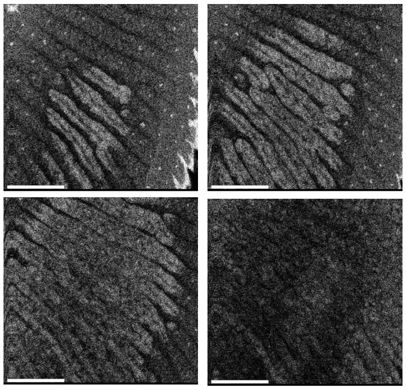

Figure 5:3-D En-face finger pad images; 760kHz A-scan. (512 A-Scans x 512 B-Scans), Scale bar: 2mm; Successive en-face images are separated by 125 um.

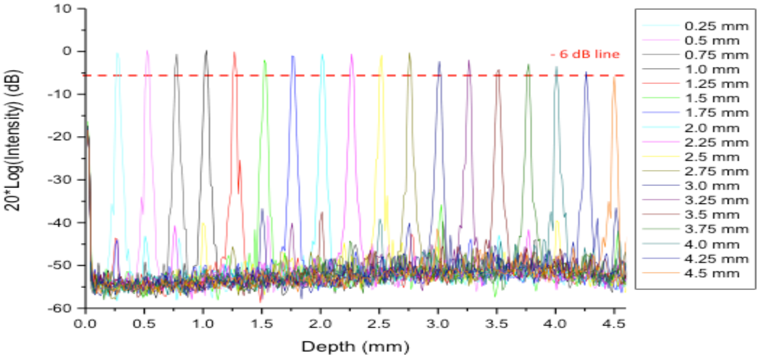

Figure 6: 500kHz A-scan OCT point spread function, consistent with >9mm dynamic coherence length, limited by electronics bandwidth.